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Flow Visualization of Film Cooling With Spanwise Injection From a Small Array of Holes and Compound-Angle Injection From a Large Array

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FLOW VISUALIZATION OF FILM COOLING WITH SPANWISE INJECTION
FROM A SMALL ARRAY OF HOLES AND COMPOUND-ANGLE
INJECTION FROM A LARGE ARRAY

by Louis M. Russell

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SUMMARY

Film injection from discrete holes in a smooth, flat surface at a pressure gradient of zero was studied for two configurations: (1) spanwise injection (30° to the surface and 90° to the mainstream) through a 4-hole staggered array; and (2) compound-angle injection (30° to the surface and 45° to the mainstream) through a 49-hole staggered array. The boundary-layer-thickness to hole-diameter ratio and the Reynolds number were typical of gas-turbine film-cooling applications. Streaklines showing the motion of the injected air were obtained by photographing small, neutrally buoyant, helium-filled soap bubbles that followed the flow field. The streakline pattern associated with spanwise injection showed a loosely wound, erratic, and turbulent vortex downstream of each injection hole. The flow was generally close to the surface but oscillated in a wave-like motion. Injection of the film at a compound angle through an array of 49 holes showed characteristics similar to those obtained previously with an array of four holes in the vicinity of these holes. Downstream, however, some of the injected flow joined to form diagonal streams whose lateral angle with the mainstream direction was greater than that of the majority of the injected flow. The lateral angle of the vortex stream leaving the holes also increased with downstream location. The additional and unique characteristics of the flow observed downstream of the first few rows illustrate that film-cooling flow-visualization investigations must include an adequate number of rows (about 7 or 8 for compound angle) to show these characteristics.

INTRODUCTION

Turbine-inlet temperature and pressure levels have reached the point where heat flux levels are too high to adequately cool hot gas-turbine components by convection

alone. Some film cooling is generally required to protect the metal parts from the hot-gas stream. The most practical method currently used for film cooling aircraft turbines is to inject cooling air from discrete holes in the surface of the blades. It is important that the air be injected in the most efficient manner possible in order to provide the desired protection with minimum disruption of the mainstream. Poorly designed film injection schemes can lead to mainstream momentum losses, which reduce turbine aerodynamic efficiency and, in some instances, even increase heat transfer to the surface.

Although experimental heat-transfer studies such as those described in references 1 to 9 have contributed to the development of analytical models of film cooling, there is a need for a better understanding of the interaction between the injected fluid and the mainstream. One method of acquiring this understanding is by flow visualization. In the studies of references 10 and 11, which used this method, the injected flow was seeded with small, neutrally buoyant, helium-filled bubbles. The paths traced by the bubbles were photographed to give streak-line patterns of the injectant mixing with the mainstream. Reference 10 presents the results of 30° in-line injection (injection through holes slanted 30° to the surface and directed in line with the mainstream). Reference 11 compares the 30° in-line results with those of normal injection (injection normal to the surface) and compound-angle injection (injection through holes which are slanted 30° to the surface and directed 15° to the mainstream).

These studies showed the characteristics of fluid elements in the jet, its lateral spreading, and its separation from the surface as the blowing ratio (mass flow per unit area of film to mainstream) exceeded critical values. Reference 11 showed that with compound-angle injection, the film remained close to the surface at blowing ratios as high as 0.9, compared with normal injection and 30° slanted in-line injection where the film separated from the surface at blowing ratios of 0.5 and above. These flow visualization studies were conducted with only four holes in a staggered array. Reference 12 reports on the relative cooling effectiveness between in-line injection and compound-angle injection on the suction side of cooled turbine vanes. These heat-transfer tests verified the superior cooling effect of compound-angle injection as inferred by flow visualization. Information that is still lacking to complete the series of studies with a flat plate in a zero pressure gradient external flow is (1) injection in a direction 90° to the mainstream at a shallow angle to the surface (spanwise injection) and (2) compound-angle injection through a large number of holes simulating a full coverage, film-cooled surface. The study with the large number of holes was required to verify that the results from the four-hole array were representative of those expected from a full coverage, film-cooled surface and to visualize the effects of additional rows of holes in the downstream direction on lateral coverage, jet interaction, and film buildup.

The purpose of this report, therefore, is to present the results of the visualization

studies of these two wall configurations. The first configuration consisted of a staggered array of four holes with five hole diameters between successive rows in the mainstream direction. The holes were oriented in a spanwise direction (30° to the surface and 90° to the mainstream). The other configuration consisted of 49 holes arranged in a 7-row staggered array with five hole diameters between rows. The holes were oriented at a compound angle (slanted 30° to the surface and directed 45° laterally to the mainstream). This configuration, except for the larger number of holes and the smaller hole size, was the same as that investigated in reference 11.

The tests reported herein were run with ambient air at about 297 K and a constant mainstream velocity of 15.5 meters per second. The pressure gradient over the test surface was zero, and the momentum thickness Reynolds number (Re_θ) just upstream of the injection holes was 2200 (ref. 11). The boundary-layer thickness to hole diameter ratio was 1.75 for the spanwise film injection and 2.04 for the compound-angle injection.

The results are presented as a series of photographs of the streaklines formed by the bubbles in the injected stream.

SYMBOLS

d	film injection hole diameter, cm
M	blowing ratio, $\rho_1 U_1 / \rho_\infty U_\infty$
Re_θ	momentum thickness Reynolds number, $U_\infty \theta / \nu$
u	velocity, m/sec
δ	boundary layer thickness, cm
θ	boundary-layer momentum thickness, cm
ν	kinematic viscosity, m^2/sec
ρ	density, kg/m^3

Subscripts:

f	film
∞	mainstream

APPARATUS AND PROCEDURE

A schematic diagram of the test facility is shown in figure 1. It consists essentially of (1) a bubble generator system, which generates small neutrally buoyant, helium-filled bubbles at a rapid rate, (2) a partially transparent plastic tunnel through which

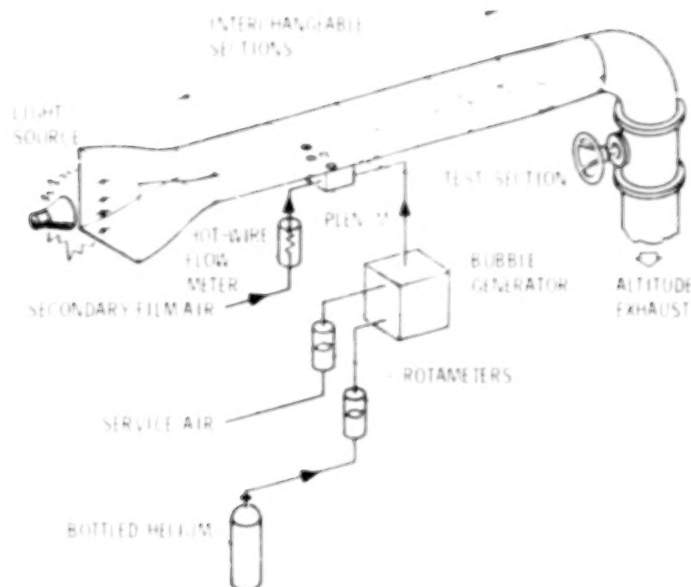


Figure 1. Film cooling flow visualization rig.

ambient temperature air is drawn into a vacuum exhaust line, (3) a plenum, which serves as a collection chamber for the bubbles and the film air, (4) a secondary air system, which is used to vary the mass flow of injected film air, (5) a high intensity quartz arc lamp, which is used to illuminate the bubbles, and (6) a test section (in the tunnel), which contains the film injection holes.

The bubble head, which is the device that actually forms the bubbles, is shown in figure 2. Reference 11 gives more detailed information about the apparatus used in this test.

Sketches of the two film-injection configurations studied are given in figure 3. The delivery tubes for the spanwise injection array had a 1.27-centimeter inside diameter and were 6.35 centimeters long. Those for the compound-angle array had a diameter of 1.09 centimeters and were 5.45 centimeters long.

Photographs of the film streaklines were taken both looking down on the test surface and from the side. The two viewing angles are illustrated in figure 4, which shows the test section with two cameras mounted in position. The top view photographs show the spreading characteristics of the film as it leaves the holes, and the side view photographs show the degree of penetration of the film into the mainstream relative to the boundary-layer thickness and the surface. For spanwise injection the side view photographs were taken with the two outer holes in the four-hole array plugged to give a profile of the two center holes. The streaklines in all the figures are black on a white background because the photographs in this report are negative images printed from color transparencies.

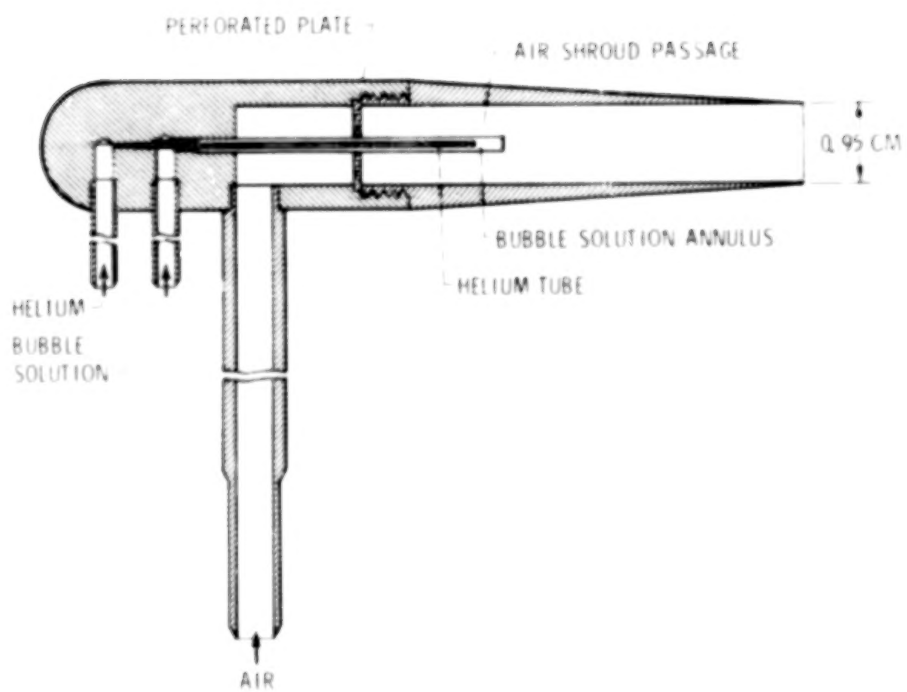
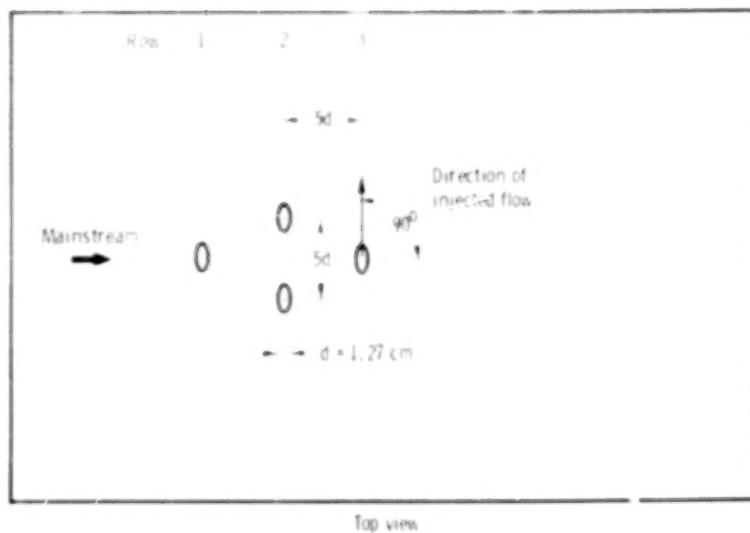
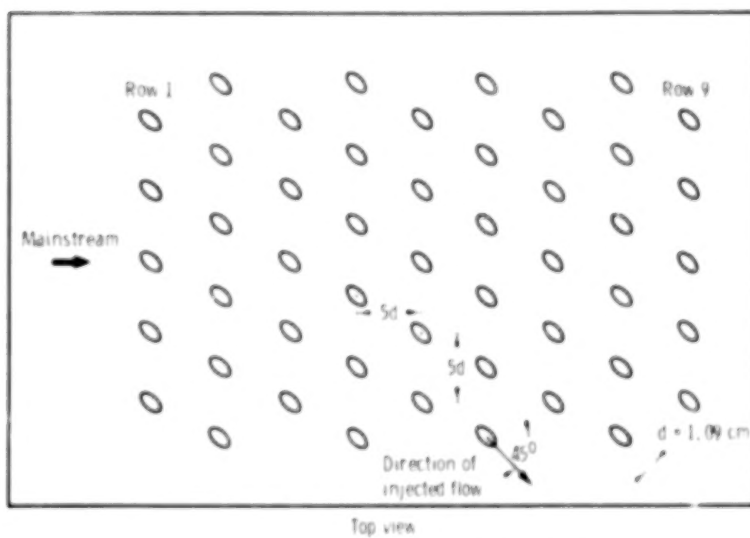
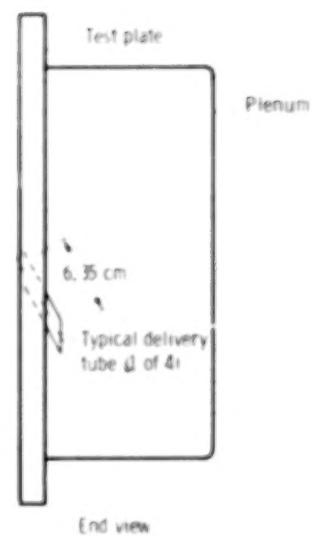


Figure 2, - Bubble generator head.



90° Spanwise.



45° Full coverage compound angle.

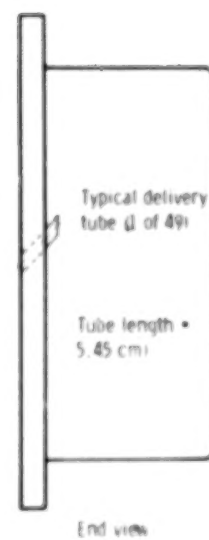


Figure 3. - Injection configurations.

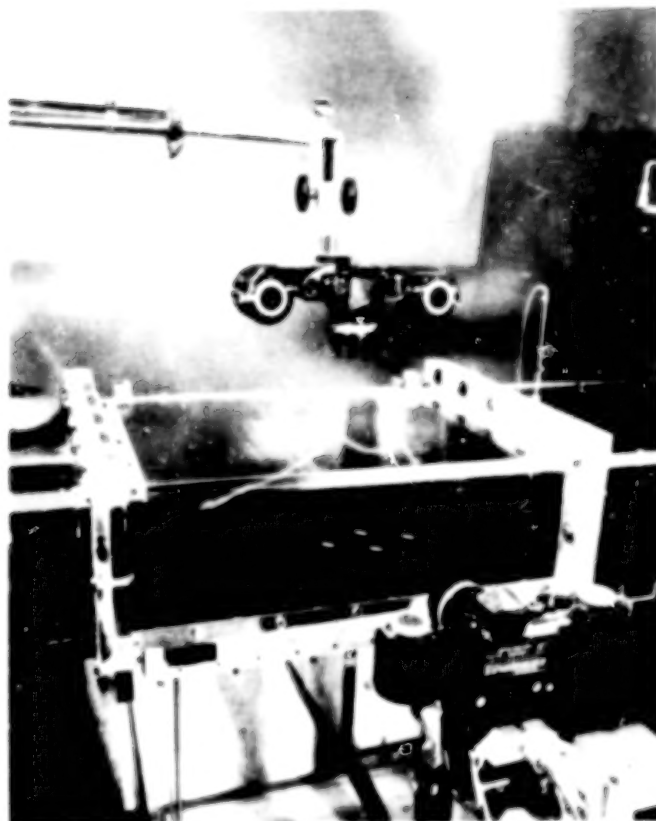


Figure 4. - Test section with top and side view camera positions.

TEST CONDITIONS

The mainstream had essentially a zero pressure gradient, and its turbulence intensity as measured by a hot wire probe was 2 percent. A turbulent boundary layer existed in the region of the film-injection holes. The velocity profile through the boundary layer was surveyed with a total-pressure probe just upstream of the injection holes. The dimensionless velocity profile through the boundary layer is given in reference 11. It is characteristic of a turbulent boundary layer on a smooth wall. The boundary-layer thickness, defined by the 99-percent value of the free-stream velocity, was 2.22 centimeters. The resulting boundary-layer-thickness to injection-hole-diameter ratio was 1.75 at the upstream injection location of the spanwise injection array and 2.04 at the upstream location of the full coverage, compound k -angle array. In both cases the boundary-layer momentum thickness was 0.215 centimeter, and the momentum thickness Reynolds number was about 2200 at the upstream hole location. These conditions are typical of gas-turbine film-cooling applications.

The film-to-mainstream blowing ratio is the ratio $\rho_f U_f$ of the injection stream to

$\rho_\infty U_\infty$ of the mainstream. Since there was negligible difference between the densities of the injected air and mainstream air, the blowing ratio is essentially the measured velocity ratio. This ratio was varied by changing the mass-flow rate of the injected film air while keeping the mainstream velocity constant at 15.5 meters per second. The blowing ratios ranged from 0.30 to 1.40 for spanwise injection and 0.30 to 1.04 for full coverage, compound-angle injection.

RESULTS AND DISCUSSION

Spanwise Injection

Streaklines traced by spanwise film injection into a turbulent boundary layer from a four-hole array are shown in figure 5. Spanwise injection produced a vortex downstream of each hole. This vortex was similar to that described with compound-angle injection in reference 11, except that the spanwise vortex was less smooth, more loosely wound, and erratic. Figure 5 shows top and side views of injection at low and high blowing ratios. Although the upper streaks rise to greater heights at blowing ratios of 0.81 than at 0.30, most of the flow remained close to the surface below the height of the boundary layer δ , as measured just upstream of the first injection hole (and indicated in the figure by the short horizontal line). There is no noticeable void in

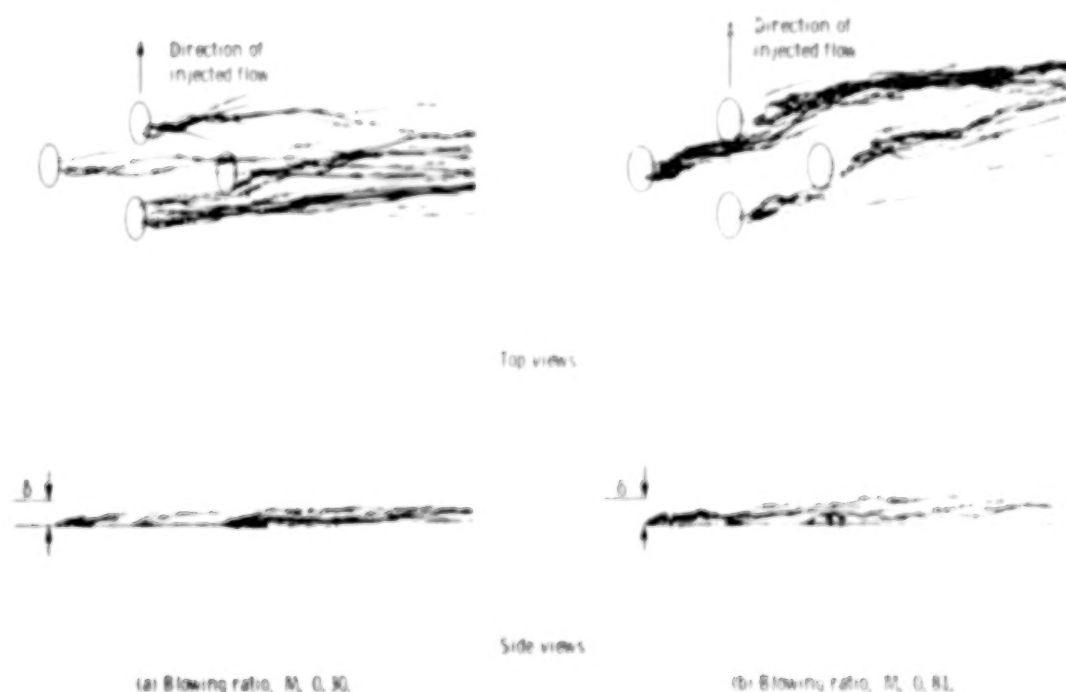


Figure 5. - Film streaklines for spanwise injection.

the flow close to the surface as was noted with in-line injection at high blowing ratios (ref. 11). A particularly evident feature of spanwise injection was that the flow oscillated in a wave-like motion as it progressed downstream. The amplitude of this oscillation increased with increasing blowing ratios.

The top views of figure 5 show the lateral spreading of the film as it progressed downstream. There were void areas in the immediate vicinity of the holes at both blowing ratios, but the void areas were larger at the higher blowing ratios of 0.81. At this blowing ratio the lateral component of the injectant caused the upstream injection streams to join with streams from the adjacent downstream rows to form essentially single streams. This resulted in voids between the streams. This effect is coincidental with this particular combination of row spacing and blowing ratio. Closer row spacing would be expected to improve lateral coverage.

All the streams from the holes started in a diagonal direction with the mainstream. As the flow progressed downstream, the angle of the coolant streams became more oriented with the mainstream direction. The spreading and coverage are better with the low than with the high blowing ratio, particularly downstream of the hole array. This coverage at the low blowing ratio was almost complete just downstream of the holes.

From a cooling effectiveness point of view, there are both favorable and unfavorable aspects of spanwise injection. The vortex created by spanwise injection held the injected coolant flow close to the surface. This should provide protection for the wall from the hot mainstream. The spreading characteristics are such that localized hot spots are unlikely except in the immediate vicinity of the first few rows of holes. However, the loosely wound and erratic vortex with associated flow oscillations and turbulence can increase local heat transfer to the surface, induce mixing of the film with the mainstream, and contribute to momentum losses.

Full Coverage, Compound-Angle Injection

Streaklines traced by a film injected into a turbulent boundary layer through compound-angle holes are shown in figures 6(a) to (d). Blowing ratios are 0.30, 0.52, 0.72, and 1.04. Although air was blown through all 49 holes, bubbles were injected through only the center four columns of holes. Attempts to inject bubbles through all 49 holes resulted in inadequate bubble density.

Injection of the film at a compound angle through the array of 49 holes showed general characteristics similar to those reported in reference 11 with an array of four holes. The distinctive feature of compound-angle injection is that the oblique angle the film made with the mainstream generated a vortex downstream of each hole. As previously stated, the vortex produced by compound-angle injection was tightly wound and smooth compared with that produced by spanwise injection, and the flow was less turbu-

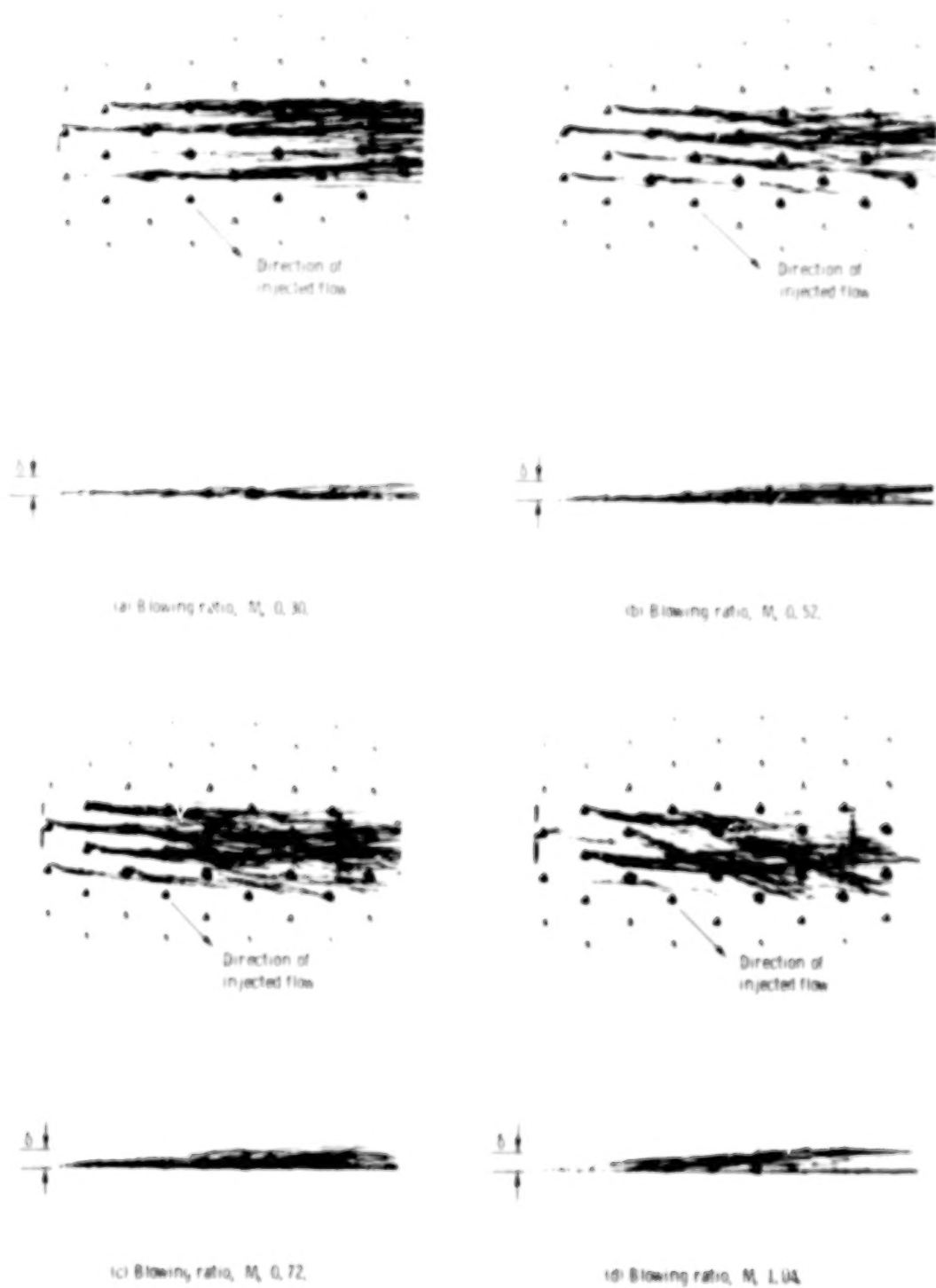


Figure 6. - Film streaklines for full coverage compound-angle injection.

lent. This vortex began forming at blowing ratios of about 0.3 and became most intense and clearly defined at blowing ratios between 0.7 and 0.9. The vortex motion kept the film close to the surface over a wide range of blowing ratios. This should provide good thermal protection. The injected flow was observed to remain close to the surface for the entire range of blowing ratios investigated ($M = 0.3$ to $M \approx 1.9$). The results in reference 11 with the four-hole array showed similar characteristics for blowing ratios up to 0.9. Although the overall film height increased somewhat with blowing ratio, the lower streaklines remained close to the surface. The height of the injected layers from the beginning of injection to the end of the first three rows is approximately the same as with the four-hole array of reference 11. As would be expected, the injected layer thickness increased with downstream distance because of the accumulative effect of injected flow from consecutive rows.

The lateral spreading of the injected flow for different blowing ratios can be seen in figure 6. At the lowest blowing ratio ($M = 0.3$; fig. 6(a)) the flow from the holes is essentially in the direction of the mainstream. Almost full use is made of the hole projected area, but there is little spreading of the film, which results in voids in film coverage on the wall areas between holes. These voids are slightly reduced at successively larger blowing ratios because of the increasing lateral departure of the injected film from the mainstream direction.

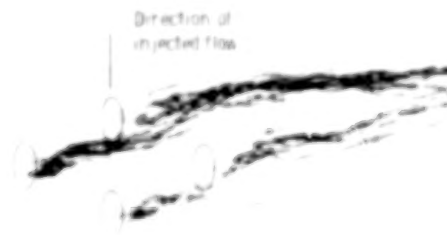
Visual observations showed the streakline characteristics of both the full coverage and the four-hole array (ref. 11) to be similar for the first few rows. Figures 6(a) and (b) show that lateral coverage was not complete until after the first six rows. At the higher blowing ratios shown in figures 6(c) and (d), complete coverage is attained after about five rows. As the flow progressed downstream, some of the injected flow joined to form diagonal streams whose lateral angle with the mainstream direction was greater than that of the majority of the injected flow. This lateral angle increased with both downstream location and blowing ratio. Although not visible in the photographs, vortex streams continued to be visually observed emanating from the downstream holes. The axes of these vortex streams increased in angle with downstream location. The action of the vortices and the angular shift of a portion of the flow contribute to more complete coverage of the surface by the film.

It was also observed that a few streaklines very close to the surface and a few out near the mainstream took paths that were skewed to the major portion of the flow. This skewed flow, along with the turbulence caused by the vortex downstream of each hole, results in undesirable mixing of the film with the mainstream. The additional and unique characteristics of the flow observed downstream of the first few rows illustrate that film-cooling flow-visualization investigations must include an adequate number of rows (about 7 or 8 for compound angle) to show these characteristics.

Comparison of Injection Angles

Figure 7 shows top views of spanwise injection at a blowing ratio of 0.81 and compound-angle injection at a blowing ratio of 0.74. The photograph for compound-angle injection is taken from reference 11. The effects of the difference between the blowing ratios are not considered significant, based on past visual observations of small differences in blowing ratios.

The relative tightness and smoothness of the vortex of the compound-angle injection compared with the spanwise injection is readily seen. The loosely wound and erratic vortex produced by spanwise injection is visually more turbulent. This turbulence increased pronouncedly with increasing blowing ratios. More voids are also apparent with spanwise injection. This is due to the way the upstream injection streams join together with the injection streams from the adjacent downstream locations. As previously stated, closer row spacing would be expected to improve this lateral coverage. The coverage downstream of the array is more complete with compound-angle injection, but it should be mentioned that more bubbles survived in the compound-angle case, producing a greater bubble density. Since the bubble density in the plenum was about the same in both cases, it can be assumed that the more difficult path followed by the



(a) Spanwise injection, blowing ratio, M , 0.81.



(b) Compound angle injection, blowing ratio, M , 0.74 (ref. 11).

Figure 7. Comparison of spanwise and compound angle injection.

bubbles in spanwise injection caused more of them to break on the walls of the delivery tubes and on each other.

The lateral coverage of the injected flow as it progressed downstream was generally better with both spanwise and compound-angle injection than with 30° slanted in-line injection (ref. 11). Reference 11 also reported that with in-line injection the film rose from the surface at blowing ratios of 0.5, which would offer little protection of the wall from a hot mainstream.

Visual observations and careful examination of figure 7 reveal that not all of the hole projected area was utilized with either spanwise or compound-angle injection before the flow was turned into the mainstream direction. More of the projected area was used with compound-angle than with spanwise injection. This can be seen by comparing the widths of the injection streams at the hole exits. This result, along with the better lateral coverage with compound injection, indicates that, for high blowing ratios, lateral injection at angles slightly less than 45° to the mainstream might produce greater utilization of the hole projected area and may provide better lateral coverage.

It may have been noticed that there appeared to be larger void areas in the first few rows of the full coverage, compound-angle array shown in figure 6(c) than in the four-hole array of figure 7(b) at a similar blowing ratio. This is due primarily to the closer camera view with the four-hole array. The closer view revealed more streaklines than in the full coverage case.

CONCLUDING REMARKS

The results of this study of film injection methods provide the designer of cooled turbine blades and vanes with a visual insight into the characteristics of the injected flow, its interaction with the mainstream, and the film coverage, all of which influence cooling effectiveness. The results show that compound-angle injection in zero pressure gradient flow generally provides better coverage of the surface with the injected film than spanwise injection and also results in less turbulence. Both of these injection methods generally provide better film coverage but result in greater turbulence than 30° in-line injection previously reported. Both compound-angle and spanwise injection are particularly effective in maintaining the injected flow close to the surface (with expected good cooling effectiveness) at high blowing ratios (up to about 0.9), compared with 30° in-line injection where the film separates from the surface at blowing ratios of 0.5 and above.

Although tests with a three-row, four-hole compound-angle array gave some insight into the characteristics of the injected flow and its interaction with the mainstream,

additional rows are required (a total of about eight) to adequately illustrate other observable characteristics, such as changes in the direction of flow and downstream film coverage.

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National Aeronautics and Space Administration,

Cleveland, Ohio, November 9, 1977,

505-04.

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